Laser Autofocusing: A Sliding Mode Approach

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***Abstract*—Quality of the laser processing depends on many factors, such as overall configuration of the laser workstation, control methods used and quality of the laser beam. Although lasers used in material processing are typically high energy lasers, light beam still needs to be focused in order to achieve higher energy density and smaller final spot size. This paper presents an application of sliding mode to the laser autofocusing system. Autofocusing system consists of photodiode as the measurement element, focusing lens and pilot laser beam. Photodiode is saturated and measurement is done in the nonlinear region of the responsivity curve. Problem of limited knowledge about the photodiodes behavior in this region is solved through sliding mode minimization algorithm. Verification of the proposed method is done experimentally.**

I. INTRODUCTION

Material processing with lasers is widely adopted in industry due to the quality and speed of the process it offers. Lasers used in material processing are typically high energy lasers with small beam waist. Nevertheless, light beam still needs to be focused in order to achieve higher energy density and smaller final spot size. Focused laser beam allows processing of smaller features and increases overall quality of the process. Work-pieces being processed with laser are not perfectly flat and usually have large surface variations that cause the change in focus of the laser light and results in uneven processing depth. Remedy to this problem is the integration of a mechanism that will automatically correct focus by moving lens or workpiece in proper direction. Factors peculiarizing autofocusing systems are speed and repeatability, due to these factors processing with same quality can be guarantied inspite of surface variations. Autofocusing mechanisms typically include measurement element, correctional controller and an actuator for the translation of lens or workpiece.

Previously several methods for autofocusing of the laser light were developed by researchers. In [1,2,3] authors present automatic focus control using astigmatic lens and four quadrant photodiode approach. Emitted laser light is reflected off the processing surface, collected by an astigmatic lens and projected onto a four quadrant photodiode. Depending on the shape of the projected beam, appropriate focusing lens adjustment is done. Method proposed by these authors is widely used in CD optics head focus control. This method is reliable but includes somewhat complex optical design and works only on reflective surfaces. In [4,5] authors present the method for autofocusing based on laser triangulation method. As a measurement tool, position sensitive detector (PSD) is used. Emitted laser beam is reflected off the work-piece surface to fall on side mounted PSD. Any height variation at the point of light reflection is sensed by PSD as lateral displacement due to configuration geometry. Relative error in position is used to actuate the lens and take proper focus correcting action. This method can deliver good results due to the PSD's high sensing resolution, however searching of the focus point has to be done off-line, empirically by trial and error. Another widely used approach to achieve autofocusing is using CCD camera to take snapshot of an image and determine the degree of defocus [6]. Beside the use of electro-optical devices to determine height variation on the workpiece surface, alternative methods are used as well. One of them is presented in [7]. In this work authors explore the pneumatic sensing device. A source of constant air flow is supplied to two separate paths. One path has resistance to air that is constant and other path has a flow resistance that is function of the distance between lens and work-piece. Relative difference between two paths is kept constant to keep the laser light at the focus. This mechanism requires the previous information about the exact desired distance between workpiece and surface of the lens.

This paper describes the laser beam autofocusing method using PIN photodiode and pilot laser light. Problem of automatic focusing is treated as a minimization problem and it is solved by sliding mode optimization technique. Implementation and verification of the proposed method is carried out on a single axis DC-motor driven mechanism using pilot laser, focusing lens and position sensitive detector (PSD). Proposed method can be used in, but is not limited to, laser processing applications. It could as well be adopted to areas of microscopy or tele-operated assembly.

The rest of the paper is organized in the following manner. In the next section theory behind proposed autofocusing system is described. In Section 3. controller design is discussed. Simulation and experimental results are given in the Section 4. and finally Section 5. contains conclusion.

II. AUTOFOCUSING SYSTEM DESCRIPTION

Concept of autofocusing system is depicted in Fig. 1. When laser beam (D) is focused with lens assembly (A) it is typically most concentrated and has the smallest waist diameter at the focal point of the lens. If the laser beam is assumed to have

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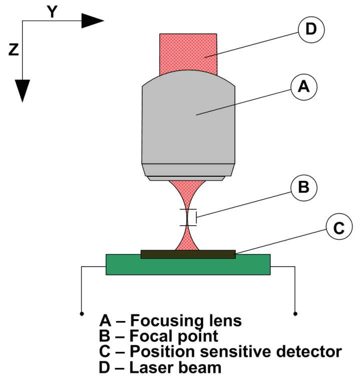


Fig. 1: Autofocusing System

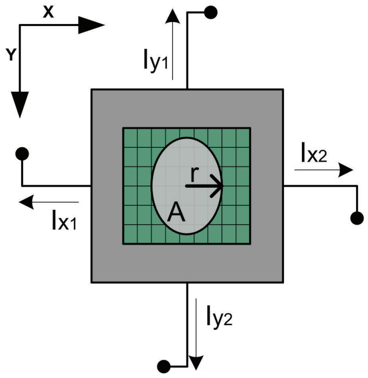


Fig. 2: Position sensitive detector

Gaussian beam profile, then due to the lens abberations, the beam is at the focus over a distance called confocal parameter (B), and not in a single point. For the purpose of autofocusing, it is necessary to find the distance between the lens surface and the workpiece such that the workpiece is positioned within the confocal parameter, and then to keep this distance constant despite of surface variations on the workpiece.

In this paper, a method for searching and preserving the location of focal point of the laser beam, in an automated fashion, is presented. As a measurement device, a 2D position sensitive detector (PSD) is used (C). PSDs are semiconductor optoelectronic devices used to determine lateral position of incident light. Typically, these devices combine position detection performance of CCD device and light irradiance measurement performance of PIN photodiodes. In this work latter one is explored.

Photodiodes have linear responsivity curve and consequently, for certain value range of incident power, the output photocurrent is linear and does not change with respect to varying size of incident light beam. However, photodiodes have a linearity limit on incident light power and can saturate if higher values are involved. If the photodiode is saturated it naturally becomes nonlinear due to high intensity of incident photons. When the device is operated in the nonlinear region of the responsivity curve, generated photocurrent becomes directly proportional to the incident beam size. If generated photocurrent density (A/mm^2) is considered to be a function of incident power distribution, total photocurrent generated can be formulated as the integral over area A shown in Fig. 2.

$$I_{tot} = 2\pi \int_0^r J(\varphi) r dr \tag{1}$$

where $J(\varphi)$ is the generated photocurrent density when light having optical power distribution φ is incident on photodiodes surface. For the case of typical Gaussian beam, power distribution can be defined as standard Gaussian distribution with zero mean:

$$\varphi = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-r^2}{2\sigma^2}} \tag{2}$$

where σ^2 is variance of the distribution and r is the distance from the center of incident laser beam. Relationship between photocurrent density and power distribution in the nonlinear region of responsivity curve could be mathematically modeled if necessary parameters of incident light beam and photodiode are known or it could be determined empirically through an experiment. Modeling of this sort would be difficult due to the uncertainties in the behaviour of the incident light beam. However, such modeling is outside of the scope of this paper. For the sake of convenience and illustrative purposes relationship between photocurrent density and light power distribution is taken to be $J(\varphi) = \varphi$. Setting $\sigma^2 = 1$, equation (2) can be rewritten as follows:

$$I_{tot} = \sqrt{2\pi} \int_0^r e^{-0.5r^2} r dr \tag{3}$$

$$= \sqrt{2\pi} e^{-0.5r^2} |_0^r \tag{4}$$

Solution of this definite integral will yield

$$I_{tot} = \sqrt{2\pi}(1 - e^{-0.5r^2}) \tag{5}$$

From (5) it is clear that the value of total generated photocurrent I_{tot} is directly proportional to the incident beam radius r. This fact is taken as the starting point in the design of the proposed autofocusing mechanism. Minimum value of the I_{tot} will be produced by minimum radius of the laser beam. Advantage of this fact is that even without having exact knowledge of the photodiodes behavior in the nonlinear region of the responsivity curve or without any offline measurement, the light spot could be minimized, thus autofocusing done. Accuracy of finding the focus point or some region inside the confocal parameter would be highly dependable on the optimization technique used. Final size of the beam waist is determined by the lens technology used.

Conceptual configuration of position sensitive detector is depicted in the Fig. 2. Device outputs four different current values depending on the light spot position on the photosensitive surface. Postprocessing of these signals is done by integrated signal processing circuits that amplify the current values and finally convert it into voltage value. The summation of the four output currents will yield the total generated photocurrent value. That can be written as follows:

$$I_{tot} = I_{x1} + I_{x2} + I_{y1} + I_{y2} \tag{6}$$

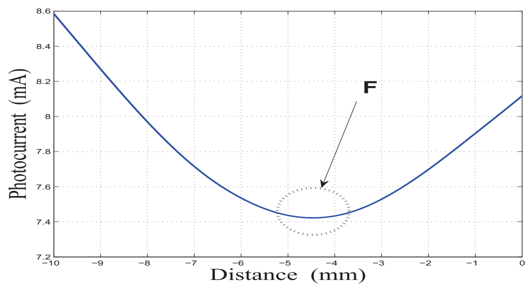


Fig. 3: Measurement of photocurrent vs. distance

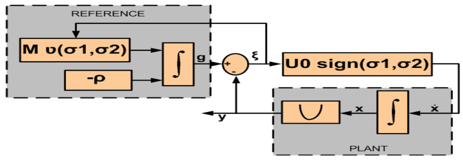


Fig. 4: Sliding mode optimization controller

Although the values of individual current values will vary with the varying position of the light spot, their sum will remain the same for a given incident power. Some manufacturers of PSDs offer the option of applying reverse biased voltage to the terminals of the photodiode. If the reverse voltage is applied, higher incident light power is required to saturate the photodiode. This option offers the advantage of canceling the noise in the signal due to the ambient light. If the PSD is used for the autofocusing purposes as discussed above than no reverse voltage bias should be applied and the PSD becomes easy to saturate even with optical powers as low as few milliwatts. This fact contributes to the ease of integration and final cost effectiveness. Fig. 3. shows the measurement of photocurrent when the photodiode is translated along the optical axis of the incident laser beam. This way photocurrent values for different beam sizes can be recorded. Measurement of the generated photocurrent is done on two-dimensional position sensitive detector, DL16-7PCBA3 from Pacific Silicon Sensor, INC, laser used in measurement is low power $5mW$ laser whose wavelength is $640nm$. Fig. 3. justifies the equation (5). Point F or some vicinity of it, is the point of interest for autofocusing purposes. In the next section method for searching and preserving region F is presented. This method uses sliding mode optimization algorithm.

III. Sliding mode optimization

A. Optimization Algorithm

In Section II. conceptualization of the photodiodes behavior in the nonlinear region of the resposivity curve was presented. In conclusion, total photocurrent generated by the incident light beam is directly proportional to the radius of the incident beam. Adaptation of the sliding mode optimization algorithm can be done in order to arrange the motion of the system in such a way that output current reaches the minimum value and stays in that point or in some vicinity of that point regardless of surface changes on specimen. Sliding mode optimization algorithm, presented in [8,9], describes the method of finding minimum point of the function by first calculating the gradient of that function and than arranging the motion of the system towards the minimum point. Formulation follows that, if given output function

$$y = f(x) \tag{7}$$

is assumed differentiable and its derivative $f'(x)\dot{x} \neq 0$ everywhere but in the point where $y = min(y)$, then the optimization algorithm can be described in the following manner:

$$\dot{x} = u \tag{8}$$

$$u = u_0 sign(\sigma_1, \sigma_2) \tag{9}$$

$$\sigma_1 = \xi, \sigma_2 = \xi + \delta \tag{10}$$

$$\xi = g - y \tag{11}$$

$$\dot{g} = \rho - M\upsilon(\sigma_1, \sigma_2) \tag{12}$$

where u is the control input to the plant defined by state coordinate x, u_0 is positive switching gain, σ_1 and σ_2 are switching surfaces, ξ is error defined as the difference between optimization reference g and measured output y. M and ρ are positive constants. Function υ is implemented as three-level relay element with hysteresis regions to avoid very high switching frequency.

Block diagram of the controller described by equations (8) to (12) is given in Fig. 4. Controller in this configuration forces error ξ to region defined and bounded by switching surfaces σ_1 and σ_2 and parameter δ. Once the value of error is inside this region the controller starts to minimize the output function y by modifying reference to the system. Minimization process is guided by the negative term $-\rho$. Once minimum point is reached controller starts to oscillate in order to keep output in a region near minimum point. In order to use such controller for autofocusing purposes, certain changes have to be made since the formulation given in [8] refers to the plant represented by single integrator.

B. Algorithm adaptation to the autofocusing system

Mechanism for the autofocusing purposes could be designed in two ways. One of them involves translating the specimen to find a focus spot, the other one involves translating the lens along the optical axis to serve the same purpose. In any case the actuation is done with AC or DC motor. Modifications to the sliding mode optimization algorithm are done for the rotational DC motor. Model of the DC motor is written as

$$\dot{x} = \omega \tag{13}$$

$$J\dot{\omega} = K_t i_{ref} - T_l \tag{14}$$

where x and ω are the position and velocity of the motor respectively, K_t is motor's torque constant, J is the motor's rotational inertia, i_{ref} is the reference current supplied to the motor and T_l represents all of the disturbance forces acting on the system. The goal of the modifications of the plant

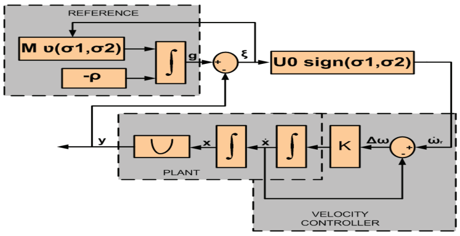


Fig. 5: Modified Controller

described by the equations (13) and (14) is to reduce the order of the system to achieve the compatibility with the formulation described by the equations (8)-(12). Constructing velocity controller as

$$i_{ref} = \frac{T_l}{K_t} + \frac{J}{K_t}(K(\dot{\omega^r} - \omega)) \tag{15}$$

where $\dot{\omega^r}$ is reference acceleration, ω is measured velocity and T_l is the estimated disturbance torque. The reference current can be written as

$$i_{ref} = i_{dis} + i' \tag{16}$$

Estimation of the disturbance torque can be done using first-order low pass filter [10]

$$i_{dis} = \frac{g_d}{s + g_d}(i_{ref} - \frac{J}{K_t}(K(\dot{\omega^r} - \omega))) \tag{17}$$

$$T_l = K_t i_{dis} \tag{18}$$

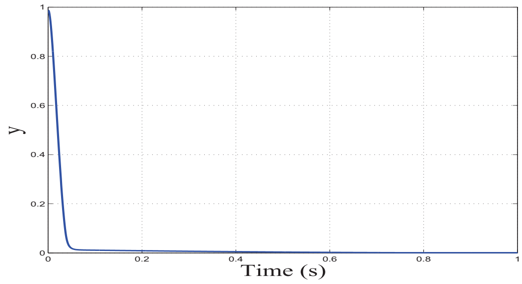
where g_d is the positive coefficient determining the cut-off frequency of the filter. Resulting velocity control closed loop behavior can be approximated as

$$\dot{\omega} + K\Delta\omega = 0 \tag{19}$$

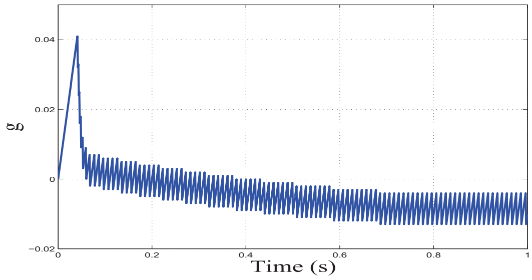
where $\Delta\omega = \dot{\omega^r} - \omega$. In the low frequency region determined by the gain K, the closed loop behavior will guaranty tracking of the reference velocity and position determined by $\dot{x} = \omega^r$. These modifications allow representation of the autofocusing system by the approximated plant as shown in Fig. 5.

IV. Simulation and Experimental Results

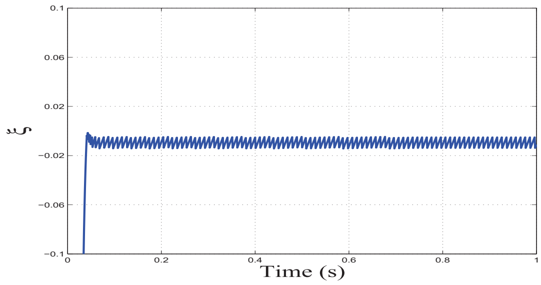
The sliding mode based minimization algorithm with the modification given by (15) is simulated and results are shown in the Fig. 6. Simulated system is depicted in the Fig. 5, in order to simulate the output of the plant, function described by (5) is used. Output taken this way will reach minimum point at 0. Output of the system, shown in Fig. 6-a, confirms the expected behavior. Motion of the system is arranged such that error, given in Fig. 6-c, between the reference, shown in the Fig. 6-b, and output of the system reaches the region defined by the switching surfaces and δ parameter. Once the error value reaches this region, the minimization process start, this can be observed in the Fig. 6-b between 0.05s and 0.7s. Once the minimum point is reached, output stays in that point. Rate by which output reaches the minimum condition is dictated by the constant ρ. Steady state oscillations in the output value are slow and can be further decreased depending on the technical



(a) Measured output



(b) Reference



(c) Error

Fig. 6: Simulation results

TABLE I: Simulation Parameters

J	$0.4gcm^2$	u_0	5
Kt	$8.26mNm/A$	ρ	2.9
M	3	K	10
δ	0.06	$Hysterisis$	0.01

requirements and design constraints. Steady state error takes the value of parameter δ. It should be noted that steady state error could be decreased by decreasing this parameter, however this could bring instability to the system. The amplitude of oscillations in the error depend on the hysteresis value of the relay.

In order to verify the usefulness of the sliding mode optimization algorithm for autofocusing purposes, experiments were conducted on an experimental system consisting of high precision linear stage, position sensitive detector and pilot laser light beam. Precision linear stage is PI's M-111.1DG DC-motor actuated Micro Translation Stage with motion resolution of $7nm$ and travel range of $15mm$. Position sensitive detector

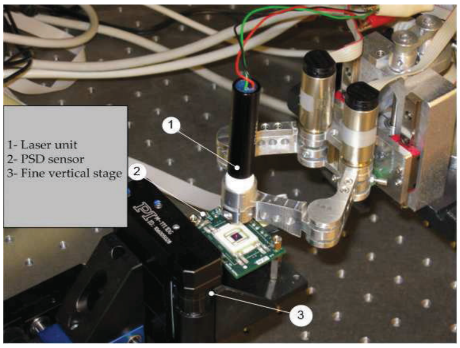
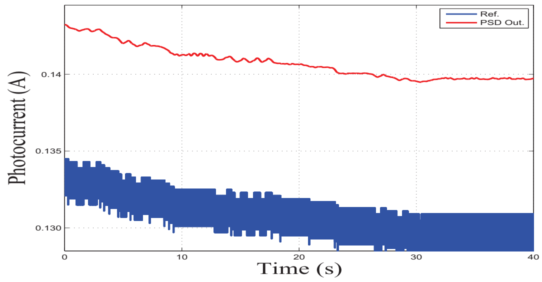


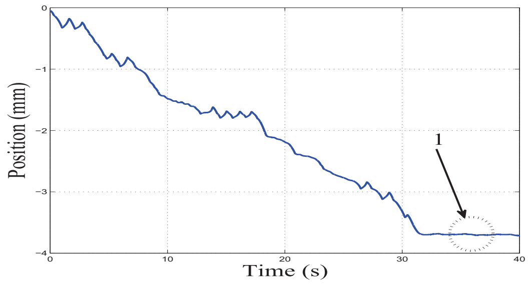
Fig. 7: Experimental setup

used is DL16-7PCBA3 from Pacific Silicon Sensor, INC. It is a 4mm x 4mm dual axis position sensing diode on a PCB with sum and difference amplifiers. Outputs are bipolar voltage analogs of the X and Y position of the light spot centroid, as well as the total photocurrent generated in X direction and the total photocurrent generated in Y direction. These sum outputs were used to measure total photocurrent generated by incident light. Pilot laser used is IMM's low power laser with optical output power of $5mW$. Wavelength of the laser is $640nm$. Laser contains the integrated focusing lens whose focal length is $20mm$. Dspace DS1005 is used as controller running with $10KHz$ sampling frequency. Output of the PSD is converted with a 16-bit AD converter and passed through a digital low pass filter with cut-off frequency of $10Hz$ to obtain smooth signal. Experimental setup is shown in Fig. 7. PSD is mounted on the translational stage in order to translate the photodiode along the optical axis of the laser lens.

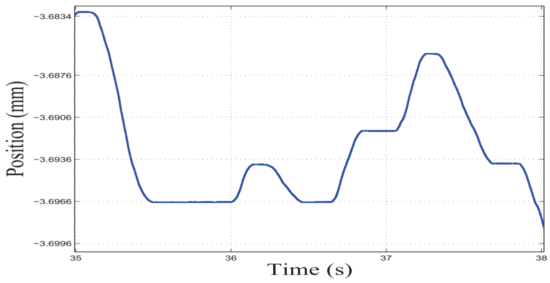
First experiment is conducted such that translational stage is initially positioned away from the focal spot of the lens. System starts to move in order to minimize output, thus reach the focal point of the lens. It must be noted that PSD is very prone to noise contamination because no reversed biased voltage is applied to the terminals of the photodiode, the reason for this is discussed earlier. Beside using very low cutoff frequency digital lowpass filter, signal levels of the output are kept low to avoid any unnecessary oscillations. Plots of the reference to the system and output of the system is shown in Fig. 8. The theoretical assumptions are verified and convergence of output to the minimum point is observed. Speed of the convergence is slow in the shown graphs, nevertheless depending on the need, careful tuning of the design parameters could result in shorter convergence time. In autofocusing applications, the convergence time can be counted up into time needed for homing procedure of the system. Fig. 8-b shows the encoder output of the translational stage and magnified plot in Fig. 8-c shows the value of the steady state oscillations. Parameter defining the amplitude of the oscillations is δ parameter. This parameters should be carefully chosen with respect to confocal parameter of the lens. As discussed before, any point inside the confocal parameter is considered to be the point of interest for autofocusing purposes so as long as the steady state oscillations amplitude is less than the confocal parameter of the lens, technical specifications can be met. In this particular experiment the steady state oscillations are about $20\mu m$



(a) Reference and Output vs. Time



(b) Encoder readout



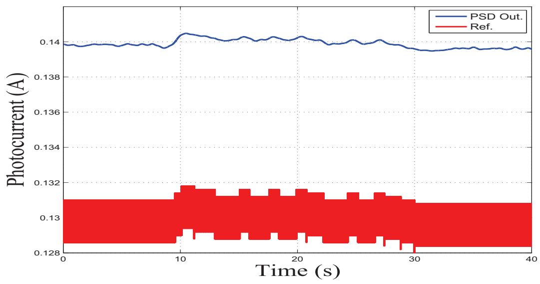
(c) 1 magnified

Fig. 8: Experimental results

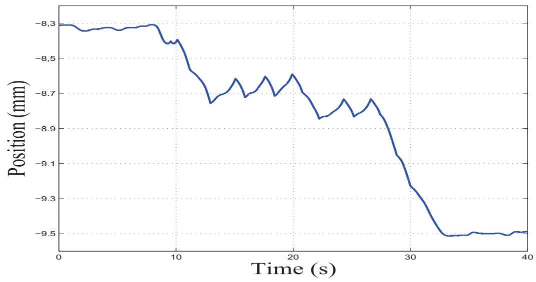
TABLE II: Experimental parameters

J	$71.1gcm^2$	u_0	10
Kt	$13.3mNm/A$	ρ	6
M	10	K	1
δ	0.01	$Hysterisis$	0.002

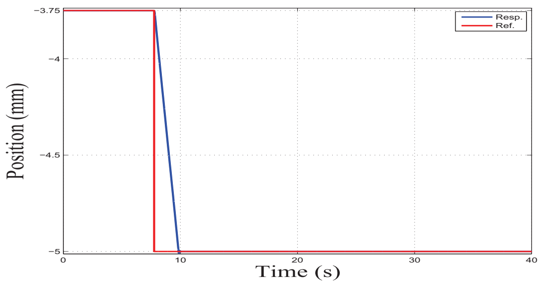
Second experiment demonstrates system response to the surface variation. Surface variation is simulated by translating pilot laser unit vertically, along the optical axis of the lens. Laser is attached on the separately controlled DC motor with optical encoder as a measurement unit. Results of this experiment are given in the Fig. 9. At the beginning of the experiment the distance between the surface of the lens and surface of the PSD is equal to the focal length of the lens and light is focused. Laser is translated along the optical axis by the arbitrary distance of $1.25mm$, Fig.9-c. Systems reference



(a) Reference and Output vs. Time



(b) Encoder readout



(c) Step response

Fig. 9: Experimental results

and photocurrent measurement is shown in the Fig.9-a. It is observed that after some time these values return back to the initial values, thus relative distance between the lens and PSD is kept constant. The encoder value of the translational stage is shown in the Fig.9-b, the difference between the initial and final value is $1.1967mm$. The absolute error between the two encoder values is $53.3367\mu m$. This error can be accounted to the fact that laser light is not focused in single spot but over a confocal parameter. The experimental parameters, given in the Table II, are kept same for both experiments.

V. Conclusion

In this paper sliding mode approach to the laser autofocusing issue is discussed. The sliding mode based optimization technique was employed in order to minimize the laser beam size. Position sensitive detector is used for measurement of the generated photocurrent by the irradiated laser light. Relationship between the value of generated photocurrent is shown to be proportional to the laser beam size and minimum spot size is reached once the value of generated photocurrent is minimum. Sliding mode approach gives opportunity to find a minimum point of the function without having previous knowledge about it, except that it is differentiable and has a single minimum. This fact contributes to reducing of the complexity of the system since no sensor calibration is needed and system is not limited to the specific type of the sensor or lens. To verify the feasibility of the proposed application, set of experiments is conducted on an experimental setup consisting of pilot laser light, PSD and high precision translational stage.

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